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# Accepted Manuscript

Cardiac arrest during space missions: Specificities and challenges

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**Cardiac arrest during space missions: specificities and challenges.**

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**Abstract**

Travelling to the stars is a dream nearly as old as mankind itself. Nowadays, spaceflight is in many ways common business, becoming even accessible to space tourists. However, many problems remain to be solved before humanity can venture into deep space with an acceptable level of risk, and medical preparedness is one of them. The management of any severe medical emergency will be extremely challenging in this extreme environment, with limited resources in crew and equipment. Here, we discuss the case of a cardiac arrest occurring during spaceflight, and present challenges around the recognition, immediate management including delivering cardio-pulmonary resuscitation and secondary measures such as organ support or evacuation. Given the current treatment capabilities in space, the survivability of cardiac arrest is expected to be lower than on the ground.

**Key-words:** CPR, microgravity, resuscitation, space flight, cardiac arrest,



## Introduction

Travelling to the stars is a dream nearly as old as mankind itself. Over the last 60 years, it became more and more real. The current presence of humans in space has produced several positive outcomes like important scientific discoveries, technological, medical as well as social advances and spinoffs for Earth's benefit. Human spaceflight facilitates peaceful international collaboration and national prestige, but ultimately our past and current experience in the space environment helps developing mitigation strategies and countermeasures which will ultimately allow us to colonize outer worlds. It has been argued that mankind had to become a multi-planetary species in order to increase its chances of surviving major catastrophic events in the future.

Today, spaceflight is in many ways common business and may even become a popular touristic destination in the years to come. However, many problems remain to be solved before humanity can venture into deep space with an acceptable level of risk, and medical preparedness is one of them. Outer space is an extremely hostile environment that can lead to the onset of specific medical conditions [1]. The management of any severe medical condition far away from the ground, beginning as close as low Earth orbit (where space stations currently reside), will be complicated by a vast variety of technical constraints. Among many other conditions, sudden cardiac arrest is of concern [2, 3, 4, 5]. Although the likelihood of cardiac arrest in the current astronaut population is low, this risk will likely increase in the future as missions become longer and more people travel into space including space tourists and their potential for co-morbidities.

Several teams have assessed the risk and proposed adapted techniques to perform cardio-pulmonary resuscitation (CPR) in weightlessness [2, 6, 7, 8, 9]. However, to

the best of our knowledge no publication discussed the whole picture, the risks and challenges associated with dealing with a cardiac arrest in space, its immediate and delayed management.

## Physiological alterations caused by microgravity

Microgravity results in many physiological alterations in the human body. Understanding the mechanisms facilitates understanding possible therapy of problems and is of utmost importance especially for long-term space flights. The most important physiological changes include bone demineralization, skeletal muscle atrophy, immune dysregulation, vestibular problems causing space motion sickness, cardiovascular problems resulting in post-flight orthostatic intolerance, and reductions in plasma volume and red cell mass [10, 11]. Also, pulmonary function is greatly altered but apparently not seriously impaired [10]. Most astronauts experience symptoms of neurovestibular acclimation during the first 1–2 days after arriving in space [11]. Acute changes in normal physiology in response to abnormal environments are labelled acclimation for short-term exposure (hours to days) or acclimatization for longer-term exposure (days to months) [11].

## Medical emergencies during space missions

Despite the immense technological performance associated with human extra-terrestrial travel, there is always the potential need for emergency medical attention [4]. Fortunately, astronaut selection, medical screening, and the limited duration of most missions have made medical emergencies rare in space [4]. Although the intensive medical selection and subsequent medical monitoring of astronauts make

medical problems unlikely during space flight, there is, nevertheless, the possibility that an astronaut in microgravity (weightlessness, zero-G) could suffer a severe medical emergency. Therefore, various studies have been undertaken to investigate the implementation of emergency procedures in space, including venous access, intubation or CPR [1, 4, 12, 13, 14].

Severe medical events in space in the history of human space flight

The specificities of the space environment have led to the development of a new medical specialty, termed “space medicine”. The expression was first coined in 1948 by the German physician and physiologist Hubertus Strughold who became the first Professor of Space Medicine at the School of Aviation Medicine (SAM) at Randolph Air Force Base, Texas.

Since the inaugural flight of Yuri Gagarin, on 12 April 1961, more than 550 people have flown to space and accumulated over 140 person-years of presence in orbit. The human endeavour in space has been marked by accidents and medical events, both major and minor. So far, 21 astronauts and cosmonauts have perished during training or space missions, but none in the space environment itself.

Luckily, most medical events experienced by astronauts have been rather minor [15]. For example, over 75% of all Shuttle astronauts have taken some form of medication for conditions typically considered non-urgent (i.e., motion sickness, headache, sleeplessness, or back pain) [4].

The spectrum of possible urgent interventions in space ranges from the initiation of chest compressions for resuscitation, to intubation [16], surgery [17] and anaesthesia [12, 18]. All the astronauts receive basic medical and first-aid responder training as part of their specialized technical training. Some are further trained to a higher level,

in their assigned role of Crew Medical Officers (CMO) [19]. In the context of future space exploration (e.g., a mission to Mars), the longer duration of missions and consecutively higher risk of incidents requiring resuscitation, increase the importance of medical techniques adapted to the microgravity environment [1, 12, 14, 20].

The future: long duration exploration missions to the Moon and Mars

The likelihood of severe medical emergencies is low; although this risk will likely increase in the future as missions become longer and more people travel into space [21]. Importantly, the expected rise of “space tourism”, where individuals screened on wealth rather than health travel to space, will only increase further the risk of serious medical events, including cardiac arrest [22, 23].

Space governmental agencies as well as private companies have outlined detailed plans for future space exploration missions to the Moon, Mars or even asteroids in the coming years or decades. According to the latest NASA mission design from 2009, a mission to Mars will most likely involve a 900-day flight of a 6-person crew, with 400 days in transit and the rest on the planetary surface [24].

The risk of a serious medical event during a mission to Mars has been estimated to be 0.06 per person-year of flight, which corresponds to one event per 2.8 years for a crew of 6 (i.e., one emergency during a flight to Mars) [4, 21, 25].

In deep space, real-time medical support will not be available because of the enormous distances involved. Indeed, the delay in communication may reach 3 to 20 minutes each way, depending on the relative position of the Earth and Mars. Therefore, the crew will need to rely solely on itself for the management of severe incidents and urgent medical events. The main concerns involve the management of severe medical conditions [26, 27], radiation exposure [28], cardiovascular

deconditioning [29], demineralisation, infections [30], as well as the psychological effect of isolation and chronic stress. The management of severe trauma and surgical conditions will imply the capability to provide anaesthesia [26, 27].

#### Risk of sudden cardiac arrest in space

Fortunately, no astronaut has ever suffered from a cardiac arrest in space and required immediate cardiopulmonary resuscitation (CPR) [31]. However, they may be at increased risk for a number of reasons. Premature atrial contractions (PACs) and premature ventricular contractions (PVCs) are seen in up to 30% of astronauts during periods of strenuous activity. Potentially serious arrhythmias (supraventricular and ventricular tachycardia) have also occurred: PACs and a bigeminal rhythm with syncope during the Apollo 15 flight, related to hypokalaemia; a 5-beat run of ventricular tachycardia onboard Skylab and a 14-beat run of ventricular tachycardia on Russian MIR in 1987, the latter was evacuated back to Earth [3]. Although rare, these cardiac events raise the concern that serious cardiac dysrhythmias could be a limiting factor during long-duration spaceflight [3].

Acute myocardial infarction is a significant cause of cardiac arrest [32]. The astronaut corps is typically composed of middle-aged men, a population at increased cardiovascular risk. Hamilton has estimated from analogue populations that the risk of acute myocardial infarction in this population could reach 0.4% per year [33]. Finally, even young and healthy individuals with no known risk factor may develop unexpected sudden cardiac arrest.

In the context of spaceflight, the loss of a single crew member may endanger the complete crew and the mission and, therefore, thorough preventive measures and onboard treatment capability should be optimised.

## Challenges of CPR in space

### Delayed recognition

Contrary to a popular belief, astronauts, unlike critically ill patients, are not monitored continuously in space, during missions often lasting several months. A collapse occurring on the ISS could easily be unwitnessed and recognised with delay only, since the station is large, noisy, and has several separate compartments. Importantly, collapsing in space would not be followed by a fall, which often represents an “acoustic warning sound” on Earth.

### Effectiveness of adrenergic agonists

Epinephrine remains a cornerstone drug in cardiac arrest resuscitation [32]. Some evidence suggests that the effectiveness of epinephrine may be altered after exposure to microgravity [13, 29]. Indeed, weightlessness induces profound changes in the cardiovascular system, in particular with regards to adrenergic receptors whose sensitivity may be lower. This, along with changes in the baroreflex and volaemia, may render the effectiveness of epinephrine and other adrenergic agents unpredictable. Earth-based models of space-related cardiovascular deconditioning are imperfect, and don't allow the development of adapted protocols [34].

### CPR techniques

One of the key issues is the implementation of adequate CPR techniques. While CPR under normal (earth) conditions is very well examined and established, various difficulties arise from its application in weightlessness or reduced gravity [35], the

main problem stemming from the absence of gravity itself leading and the lack of a thrust block for performing chest compressions [6]. Without this, attempting compressions of the chest in microgravity only leads to the 2 individuals moving away from each other, without achieving any haemodynamically significant cardiac output in the patient.

So far, five separate methods for CPR in space have been described [2, 36]. However, it remains unclear which of these techniques could provide the best quality CPR in space. Depending on the scenario and the number of people available, different techniques could be recommended (Fig. 1 to 4) [2].

- Standard side straddle (STD) method: The rescuer places himself sideways and the patient is situated on the crew medical restraint system (the foldable stretcher of the ISS) for CPR.
- Waist straddling manoeuvre (SM): The rescuer straddles the patient's waist, with the patient situated on the crew medical restraint system for CPR.
- Reverse Bear Hug (RBH) method: The rescuer grips the patient from the back with both arms and performs chest compressions.
- Evetts-Russomano (ER) method: In the ER method, the practitioner places himself on top of the patient, with his left leg over the right shoulder of the patient and his right leg around the patient's back under the left arm. The chest compression applied against the sternum is countered by the force exerted by the practitioner's crossed legs.
- Handstand (HS) method: To carry out the HS method, the practitioner places his feet on one wall of the cabin, with the patient's back against the opposite wall, and the chest compressions are applied against the sternum.

Performance of CPR techniques

Judging the quality of CPR relies primarily on factors such as compression depth and compression frequency [32]. In comparative studies, significant differences among the various methods were found in both the depth and the rate of chest compressions [2].

Different methods have been proposed to simulate CPR in microgravity, including parabolic flights, decubitus, or a body suspension device (BSD; Fig. 5) [2, 6, 7, 8, 9].

Unlike parabolic flights where time in weightlessness is limited to about 20 seconds per parabola, the BSD allows longer studies. Since several experiments were carried out during parabolic flights, the data for prolonged CPR is incomplete and it remains unclear whether the methods tested could allow provision of good quality CPR for a longer period of time. Additionally, the aerobic capacity of astronauts is reduced in space, which may impede further the quality of CPR [19].

With the HS technique, the requirements for compression depth according to earth CPR guidelines could almost be achieved [2]. The RBH and the ER technique also show good results with respect to compression depth. While carrying out resuscitation in a kneeling position next to the patient is the standard method for CPR under earth conditions, both conventional techniques (STD and SM) show broad deviation and did not allow to achieve chest compressions of adequate quality. In total, however, none of the examined techniques achieved the requirements of the current CPR guidelines [32].

Besides compression depth, compression rate (CR) is an important factor for achieving an adequate cardiac output during CPR [32]. Here, four out of the five techniques achieved the required compression rate, with only the RBH method failing [2].



Another surrogate for CPR quality is the estimated cardiac output, which can be calculated from compression frequency and compression depth [2]. Here, the HS method followed by the ER technique were found to be superior to the other techniques [2].

Due to the impossibility of conducting CPR studies *in-situ* in space, parabolic flights and ground-based simulations, such as those using a BSD, have been used to fully comprehend the efficacy and benefits of the most common extraterrestrial CPR methods [35]. These simulations, however, come with their own limitations related to the volunteer and CPR dummy used, and these must be understood to allow proper conclusions to be drawn regarding the application of different CPR techniques in space.

The data provided by these studies focus on the mechanical aspects related to the performance of external chest compressions, including chest compression depth and rate, as well as the fatigue of the volunteer performing CPR, which seems to increase proportionally to the decrease in gravitational force simulated [8, 9]. Although parabolic flights have a time restriction for the microgravity phase of each parabola, it does provide a more realistic experience because the volunteer feels a lack of body weight, just as would be encountered in a space mission. It also allows some displacement of blood and body fluids from the lower to the upper body, which is more representative of the cardiopulmonary changes that occur during actual microgravity exposure and might influence the CPR performance [9]. The use of a BSD prolongs the duration of the CPR performance, with no time restriction for its use. This method can provide different levels of apparent body weight of the volunteer, ranging from the microgravity to hypogravity of the Moon and Mars, however, there is no simulation of the cardiopulmonary physiological changes that

will occur in these types of environment [6, 7, 8]. Furthermore, parabolic flights and BSD use as CPR simulators do not consider the skeletal muscle atrophy and consequent decrease in strength that might be present in space missions, especially those of long duration. In addition, the CPR dummy itself that represents the astronaut in cardiac arrest must be considered. This device is unable to reproduce the alteration in chest shape that occurs in reduced gravity environments, with the chest becoming more rounded, increasing the distance between rib cage and the heart, which in turn can affect the ideal chest compression depth for a successful CPR. The CPR dummy is unable to replicate the physiological effects on the cardiopulmonary system seen during actual microgravity or hypogravity exposure, which also potentially have an effect on CPR performance and/or outcome [35].

## Mechanical resuscitation devices

Besides manual compression, the use of mechanical devices like LUCAS or AUTOPULSE is common for CPR under special circumstances for both in-hospital and out-of-hospital emergency medicine on earth [32]. Since quality and performance of CPR in microgravity is lower as compared to earth, there are some very few experimental approaches for using mechanical devices during microgravity so far [37]. Of course, CPR adjunct devices would positively impact resuscitative procedures like CPR by small crews with inherent manpower requirements. On the other side, since the risk for CPR is quite low, it is questionable to place a mechanical CPR device in space, e.g. because of costs and weight.

## Post-ROSC treatment

Due to the exceptional external circumstances (e.g. absence of gravity, limited skills and equipment available, cramped conditions) it is unlikely that CPR could achieve the same level of performance and similar outcomes in space when compared to earth [33]. Even under ideal conditions (immediate recognition and initiation of CPR, ideal technique, rapid defibrillation) the return of spontaneous circulation (ROSC) is only achieved in a meagre fraction of patients on earth. In space, the expected outcome will be aggravated by the fact that currently very few opportunities for subsequent intensive medical therapy exist.

The current medical kit onboard the ISS is limited and will need to be profoundly updated for future space exploration missions. Nowadays, medical equipment and consumables on the International Space Station (ISS) are organised in 6 large packs, the ISS Health Medical System, with a total weight of 31 kg and a volume of approximately 130 litres. The whole kit was updated in 2011 and now comprises 190 medications, a foldable stretcher/examination table (the Crew Medical Restraint System), a semi-automatic defibrillator, a simple and robust respirator (Autovent 2000, Life Support Products Inc.) and an ultrasound machine (GE Vivid q), with a specially designed keyboard overlay to facilitate tele-guidance from the ground. The kit allows provision of routine minor medical needs, as well as basic and advanced life support [38]. A separate medical kit also exists in the Russian segment of the ISS. Non-invasive testing using pulse oximetry, end-tidal CO<sub>2</sub>, impedance cardiography, and echocardiography have been evaluated during spaceflight [4].

While obvious restrictions in storage capacity have dictated the contents of the in-flight medical kits [4], another major limiting factor is the shipping cost, which has been estimated at around \$10,000 per pound for launching equipment aboard the

ISS [4]. In these circumstances, it is obvious that the provision of both the etiological treatment of the condition leading to cardiac arrest (e.g. coronary angiography, thrombolysis, correction of profound hypovolaemia or electrolyte disturbance) and post-ROSC therapies (prolonged sedation, targeted temperature management, mechanical ventilation, organ support, anti-infectious therapy) may not be achievable.

Evacuating a critically ill individual from the ISS is most likely impossible given the current configuration of space vehicles [19]. To travel to and from the ISS, the only available spacecraft in 2017 is the Russian Soyuz, in which 3 individuals cram themselves in tiny seats, wearing pressurized suits and enduring gravity levels of up to +9G during re-entry, all conditions incompatible with the transportation of an unstable patient.

Besides CPR on ISS, it is also likely that a cardiac arrest occurs during space tourism activities. The risk might be higher since tourists may have more severe pre-existing diseases. Time to return to earth is also quite different (minutes) for private-funded space tourism as compared to government-financed spaceflight (e.g., to ISS or Mars). However, treatment options are significantly limited in both types of spaceflight. However, after CPR during space tourism, returning to earth is “unpreventable” and takes only some minutes. Therefore, the probability to survive is different.

On the other side, during long-term spaceflight, CPR is possible but it is questionable how long it should be performed and how to treat a person with ROSC. Since ICU therapy is usually not possible for more than a few hours in space due to limited resources, the medical problem rapidly turns into an ethical issue: What type of therapy should be done, when should it be stopped or should it even be started?

Naturally, the question arises of whether CPR should be provided at all in space. It has been stated previously that the crew of space exploration missions had to prepare for non-survivable illnesses and difficult ethical questions such as withdrawal of care.

## Conclusion

Nowadays, spaceflight is in many ways common business, even becoming occasionally a touristic destination. However, many problems remain to be solved before humanity can venture into deep space with an acceptable level of risk, and medical preparedness is one of them. The likelihood of cardiac arrest occurring in space remains extremely low, and will most likely be non-survivable due to several factors including delayed diagnosis and difficulties in immediate and secondary management.

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**Fig. 1:** Different techniques of CPR during microgravity using straddles. Here, ESA astronaut Paolo Nespoli practices the waist straddle method onboard the ISS.

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**Fig. 2:** Reverse Bear Hug (RBH) method (Photo: NASA, public domain).





467 **Fig. 3:** Evetts-Russomano (ER) method (Photo: ESA, public domain).

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471 **Fig. 4:** Handstand (HS) method (Photo: NASA, public domain).

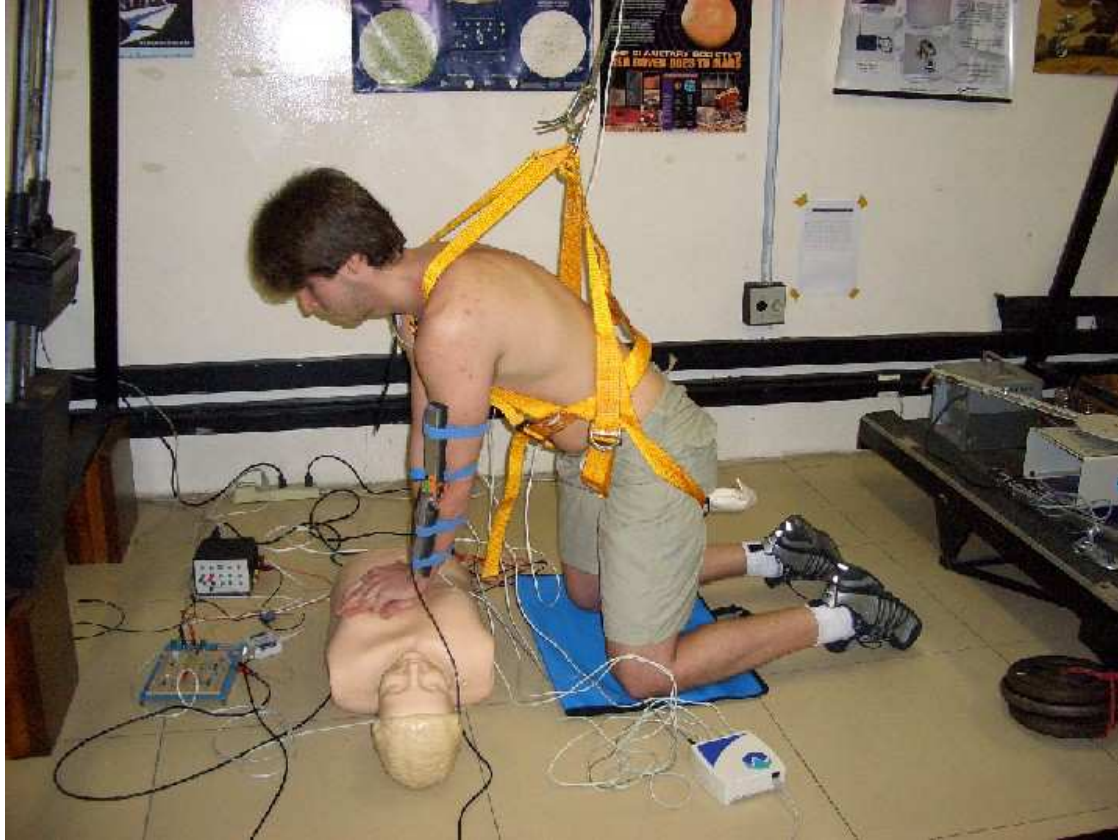
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**Fig. 5:** Body Suspension Device (BSD) to simulate microgravity for CPR (Photo: Thais Russomano).



## Highlights

Nowadays, spaceflight is in many ways common business, becoming even accessible to space tourists.

The management of any severe medical emergency will be extremely challenging in this extreme environment, with limited resources in crew and equipment.

Given the current treatment capabilities in space, the survivability of cardiac arrest is expected to be lower than on the ground